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IMPLEMENTING A NEW EFFECTIVE FINITE DIFFERENCE FORMULATION FOR BOREHOLE HEAT EXCHANGERS INTO A HEAT TRANSPORT CODE

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ABSTRACT

We present an effective finite difference formulation for implementing multiple ground heat exchangers (GHE) in the 3-D coupled heat and flow transport model SHEMAT (Simulator of Heat and Mass Transport, Clauser, 2003) The GHE with arbitrary length can be coaxial as well as U-shaped.

The new approach does not require the fine discretization of the GHE assemblage since it considers heat transport between fluid and the soil through pipes and grout via thermal resistances. Therefore, the simulation time can be significantly reduced.

The coupling with SHEMAT is realized by introducing an effective heat generation. Due to this connection, it is possible to consider heterogeneous geological models, as well as the influence of groundwater flow. This is particularly interesting when studying the long term behavior of a single GHE or a GHE field. The model is validated against the existing GHE modeling codes EED and EWS. A comparison with monitoring data from a deep GHE in Switzerland shows a good agreement. A synthetic example demonstrates the usages and field of application of this new numerical tool.

INTRODUCTION

There are several different numerical tools regarding the modeling of system performance of ground heat exchangers (GHE), e. g. the Earth Energy Designer (Hellström, 2000), or the code EWS described in Huber (2007). A realistic prediction of the long term behavior helps to design the GHE according to the desired requirements. However, the aforementioned codes only consider a conductive thermal regime which does not take into account the influence of groundwater flow. Since advection contributes to subsurface heat transport, it must be taken into account in areas where groundwater flow is significant. Furthermore, the extreme geometrical aspect ratios, typically involved in geothermal heating systems, make the numerical analysis complicated and computationally very demanding.

IMPLEMENTATION IN SHEMAT

The code SHEMAT solves coupled problems involving fluid flow, heat and mass transport on a finite difference grid. Additionally, it can handle chemical water-rock interactions. Therefore, it can be applied for a variety of thermal and hydrogeological problems (see Fig. 1).

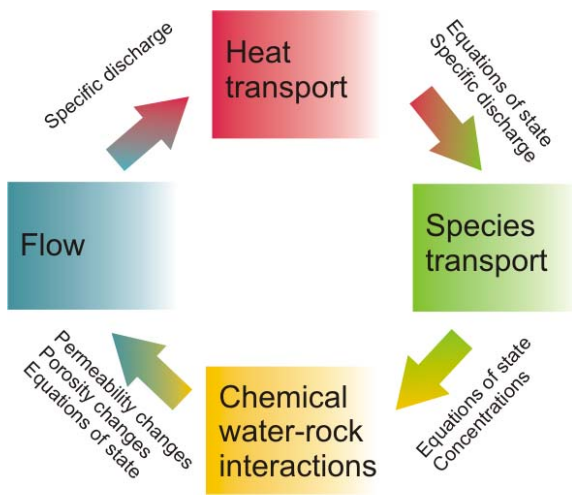

Figure. 1. Overview of the different processes which can be simulated with the code SHEMAT.

The Finite Difference formulation of the new approach involves the determination of thermal resistances of the different parts of the GHE. The coupling SHEMAT is realized by introducing an effective heat generation. Due to this connection, it is possible to consider an arbitrary, heterogeneous geologic model, as well as the influence of groundwater flow. The inlet temperature as well as the pump rate can be chosen according to individual requirements. The numerical simulations show that the additional computing time, which is needed for modeling the new GHE module, is negligible.

Therefore, the available computing power limits the number of nodes in the 3-D model under consideration. Fig. 2 shows a sketch of a coaxial ground heat exchanger, as well as the schematic FD approach. U-shaped GHE can be modeled as well, but the determination of thermal resistances is not trivial in this case, therefore we use an approach of Hellström (1991).

Fig. 3 illustrates the placement of one or several GHE in a 3-D model. Thus, the new approach is applicable for simulating GHE fields, since there is in principle no restriction in the number of GHE in a model run.

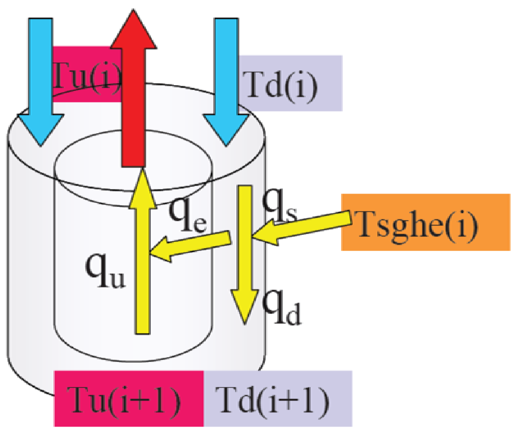

Figure. 2. Finite Difference approach for calculating heat flow q and temperatures T (here coaxial).The subscripts u and d denote up and down flow, respectively, q_e is heat flow from the outer to the inner pipe, and q_s the one from the surrounding with temperature Tsghe.

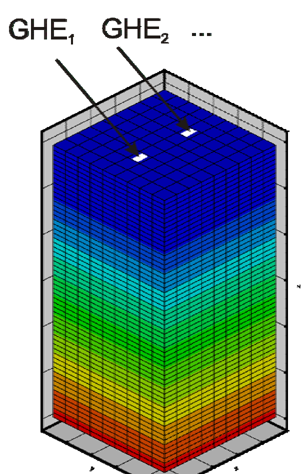

Figure 3. A GHE is placed anywhere in a 3-D model, defined by the ith and jth node.

COMPARISON WITH EXISTING MODELS AND DATA

In order to validate the new approach, we first compare it to the existing models EED and EWS. To this end we set up a model with a shallow double U-shaped GHE in a homogenous subsurface. Table 1 shows the model's properties. While EWS uses semi-analytical solutions and calculates inlet and outlet temperatures, EED only gives a mean fluid temperature along the entire GHE as a monthly average. The equations are solved analytically. Thus, Fig. 4 shows not only inlet and outlet temperatures, but also mean values. The difference between this line and the EED temperatures is about 1 K, but both lines nearly show a steady state situation after 10 years. Regarding the EWS temperatures, the difference is of the same order at this time. However, the lines are not parallel, implying that the EWS temperatures are not in steady state yet. Furthermore, the difference between the existing models is even larger, but keeping in mind the different approaches (analytical and Finite Differences), the deviations seem acceptable.

Table 1. Properties of the GHE used for comparison.

Parameter	Wert
Bore hole diameter	0.12 m
Pipe diameter, thickness	26 mm, 3 mm
Pipe thermal conductivity	0.4 W m^{-1} K^{-1}
Length	20 m
Flow rate	0.108 m^{-3} h^{-1}
Fluid	Water
Power (constant)	300 W
Ground thermal conductivity	2.4 W m^{-1} K^{-1}
Grout thermal conductivity	2.4 W m^{-1} K^{-1}
Ground thermal capacity	2.6 MJ m^{-3} K^{-3}
Simulation time	10 years

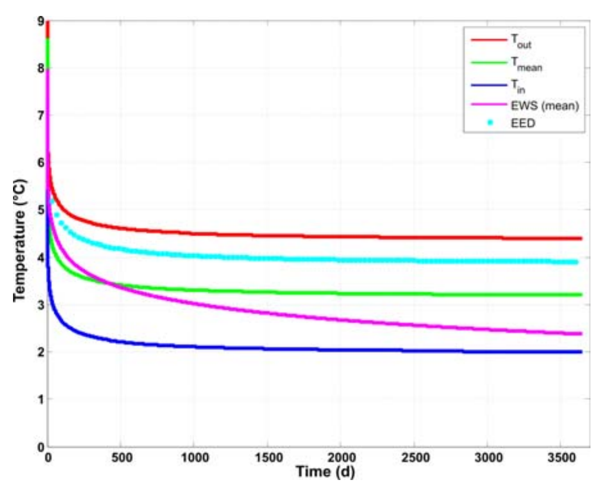

Figure 4. Comparison of the modeled temperatures with the codes EED and EWS.

In a second model, the thermal load of a GHE is varied according to some annual profile. (Figure 5 and Table 2). This model is taken from a study in Signorelli (2004). Here, a similar deviation is observed, compared to the first example.

Table 2. Properties of the GHE after Signorelli (2004).

Parameter	Wert
Bore hole diameter	0.115 m
Pipe diameter, thickness	32 mm, 5.8 mm
Pipe thermal conductivity	0.42 W m^{-1} K^{-1}
Length	100 m
Flow rate	1.476 m^{-3} h^{-1}
Fluid	Water-Ethylenglycole (20 %)
Power (constant)	208 W – 2070 W
Ground thermal conductivity	2.46 W m^{-1} K^{-1}
Grout thermal conductivity	0.81 W m^{-1} K^{-1}
Ground thermal capacity	2.6 MJ m^{-3} K^{-3}
Simulation time	10 years

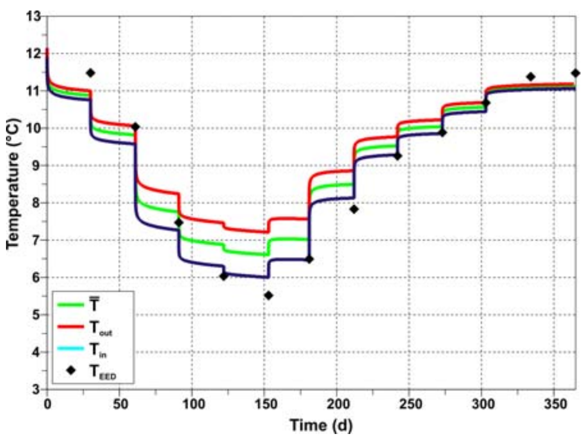

Figure 5. Comparison of the new approach with a EED model presented in Signorelli (2004). Simulation begins in September.

In a last model, we compare our model to monitoring data from the deep GHE in Weggis, Switzerland. Figure 6 shows its assemblage. During several years, inlet and outlet temperatures, as well as the pump rate were monitored (Eugster und Füglister, 2003). In Fig 7 we plot a comparison for the year 2000. The blue line represents the model's inlet temperature which was interpolated using the data (blue dots). There is a good agreement between the measured and modelled outlet temperatures.

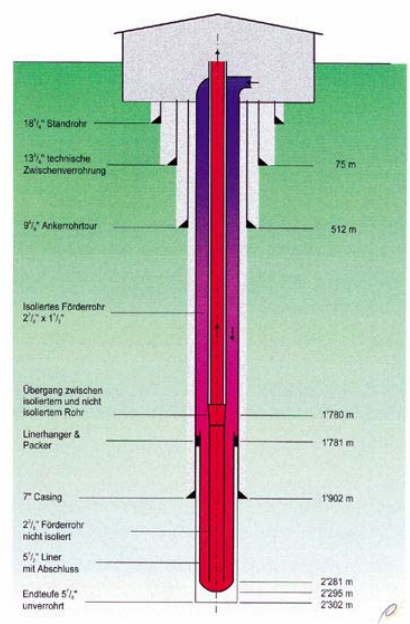

Figure 6. The deep GHE in Weggis, Switzerland

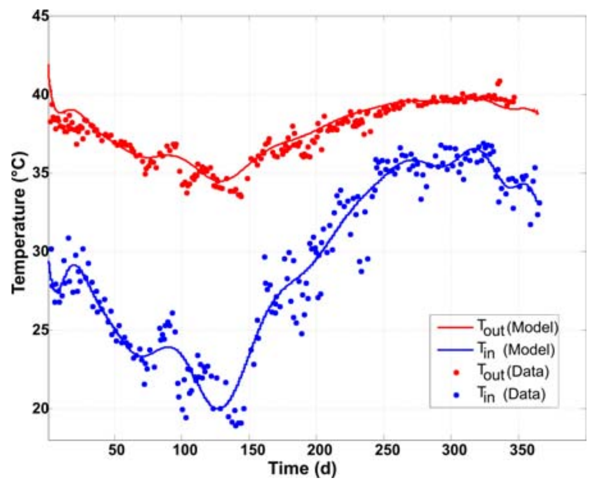

Figure 7. Comparison with monitoring data from the deep GHE in Weggis, Switzerland (Eugster und Füglister, 2003)

SYNTHETIC EXAMPLE

In order to study the influence of groundwater flow, we set up a 3-D model with a 100m GHE whose properties correspond to the example given in the last section (Table 2). However, in this case we fix the inlet temperature at 5 °C and the whole model domain is affected by groundwater flow at a Darcy velocity of 30 m a^{-1}. This allows quantifying the influence of groundwater flow in terms of the outlet temperature, when compared to the same model without groundwater flow. Fig. 8 shows that enough heat is advected by flow to reach a constant outlet

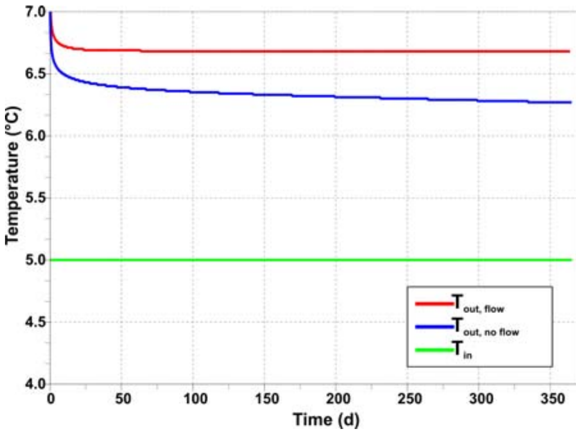

Figure 8. The influence of groundwater flow on the outlet temperature of the modeled GHE.

temperature after 50 days. In the conductive model there is still no steady state behaviour after one year.
The resulting temperature field in both cases is plotted in Fig. 9. When groundwater is present, the asymmetric temperature field is clearly visible.

CONCLUSION AND OUTLOOK

We present the coupling of a finite difference formulation of GHE with the general code for heat and transport modeling SHEMAT. The connection between these two numerical approaches on different scales is realized by introducing an apparent heat generation in SHEMAT. Thus it is possible to consider an arbitrary, heterogeneous geologic model, as well as the influence of groundwater flow in the surroundings of one or multiple ground heat exchangers. The new model is validated against existing models and field data, showing a satisfactory agreement. Future work aims at a reduction of computing times. This requires an optimization of the code. Additionally, further comparison with data monitored in running ground heat exchangers is necessary for further validation.

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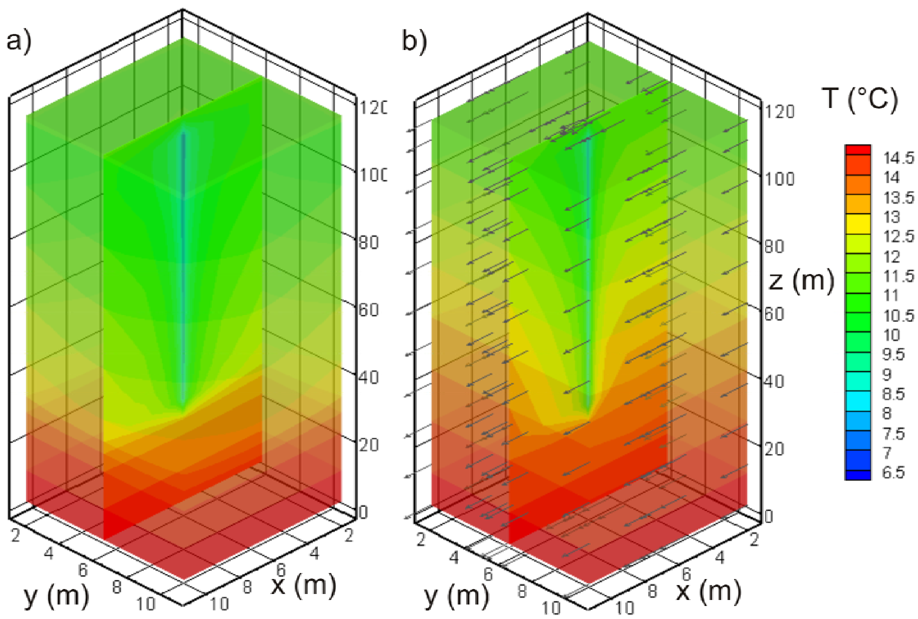

Figure 9. Temperature field of the synthetic model in order to study the influence of groundwater flow (a) Conductive model (b) Model including flow at 30 m per year.